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ADVANCED DUMMY INSTRUMENTATION AND STANDARDS FOR NINE-ACCELEROMETER ARRAY

by

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Introduction

The Transportation Systems Center (TSC), Research and Special Programs Administration, is engaged in a number of activities in support of the Crashworthiness Division, National Highway Traffic Safety Administration (NHTSA). The activities include:

1) Support to Advanced Dummy Development
2) Calibration Technology Assessment
3) Accelerometer System Standard

Support to Advanced Dummy Development

In support of the NHTSA's activities to develop an advanced anthropomorphic test dummy (ATD), a review was conducted of alternative instrumentation to measure the forces and kinematics experienced by dummies during automotive crash tests. As part of this work, a preliminary review of available sensors, signal conditioners and data acquisition systems was carried out for TSC by Arthur D. Little, Inc. (ADL). One of the major objectives of the review was to explore the potential for placing much, if not all, of the instrumentation within the dummy itself. Although many components have been reduced in size in recent years, it was realized that volume constraints would be the biggest problem in placing instrumentation within the dummy.

The most well instrumented ATD in current use is the Hybrid III dummy. The Hybrid III instrumentation system has been viewed throughout this effort as the baseline upon which to build and develop a more advanced system. It is clear that, for the most part, the sensors used in the Hybrid III dummy represent the state-of-the-art for such instrumentation. This is partly due to the fact that some of the sensors used are custom built for this particular purpose rather than adapted from more general purpose instruments. In almost every case, it is acknowledged that the particular sensor being used in the Hybrid III is as good as or better than anything else available for that purpose but also that there may be room for improvement.

Current practice in signal conditioning is an area which has considerable room for improvement. The requirements for the signal conditioning equipment are to provide power to the sensors, provide anti-aliasing filtering for each channel and provide amplification of the signal for each channel. There are few items available that provide all of these functions simultaneously and are at all suitable for use on board the dummy. Even those that provide a complete signal conditioning function require external components for filter tuning and other functions, and the shock specifications for these devices are uncertain. While there are many sources for monolithic integrated active filters, these also require the use of additional components to adjust the frequency and gain of the filter, increasing the volume consumed considerably. There are a few potted hybrid filter circuits available that do not require additional components for operation but they are relatively large. The choice of whether or not the signal conditioning will be mounted within the dummy will depend greatly on the degree to which this hardware can be hardened for the expected environment and the available volume in the dummy.

Data acquisition methods represent the greatest potential for improvement in the advanced dummy development. Methods to date have typically consisted of routing analog information from sensors on the dummy through a large umbilical cable where it is then multiplexed and recorded on an FM tape recorder. Post test, the data is processed through anti-aliasing filters which usually have the characteristics specified in SAE Recommended Practice J211 for class 1000 data. Generally, the data is then digitized and further processed by digital computer and stored on digital tape in an NHTSA specified format. There is concern that the large umbilical cable used may interfere with the response of the dummy in certain crash tests. The desire is to reduce the size of the umbilical cable while maintaining reliability.

Several alternative data acquisition systems and methodologies were identified as suitable for use with anthropomorphic dummies. The selection methodology is illustrated in Figure 1. Both on-board (on the dummy) and off-board (on the test vehicle) storage of data were considered. All of the on-board storage systems

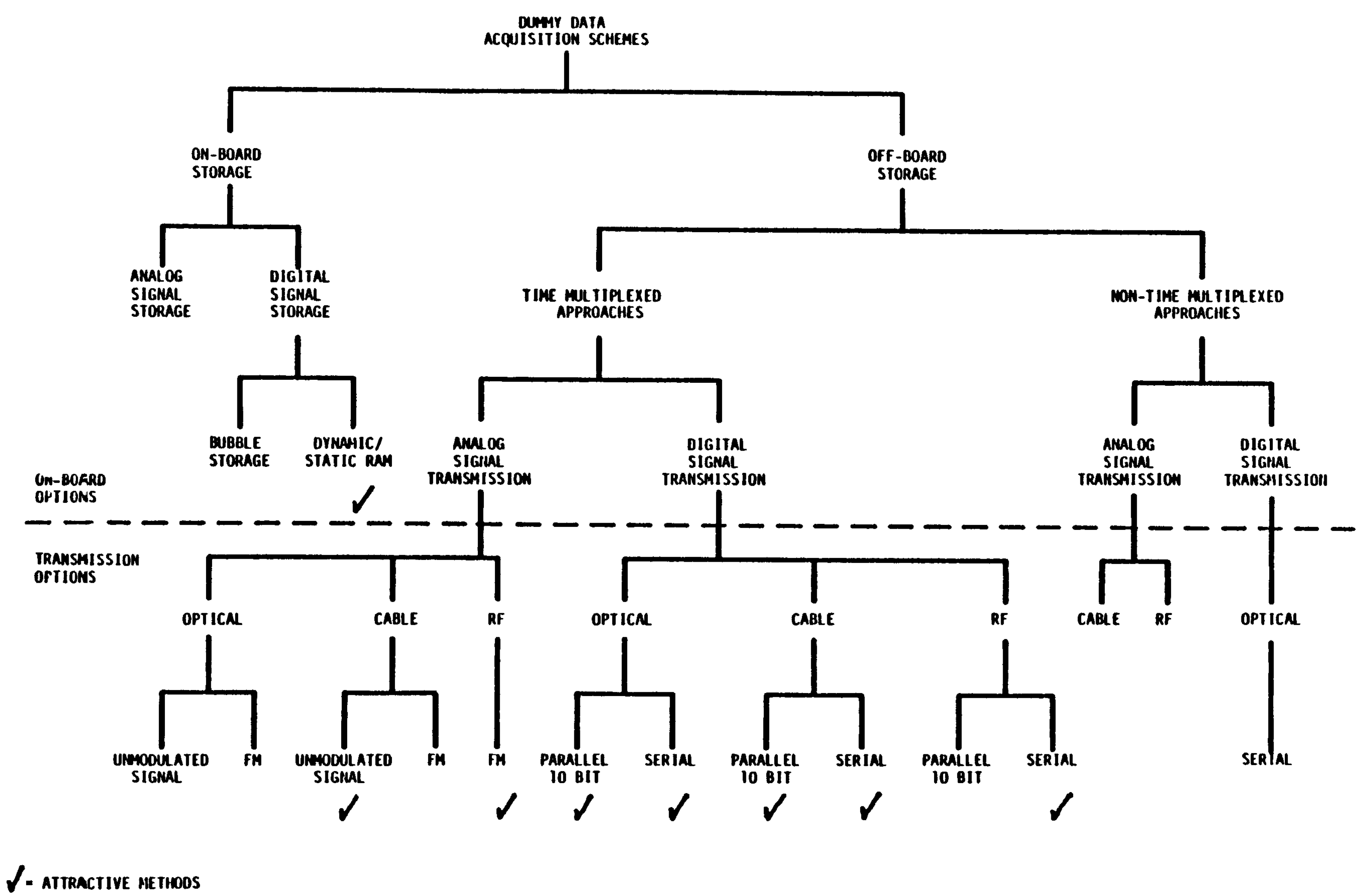

FIGURE 1 - DATA ACQUISITION ASSESSMENT

contained the following elements:

1. Data sampling
2. Analog-to-digital (A/D) conversion
3. On-board digital storage
4. Acquisition controller
5. Parallel to serial data conversion

The schemes for on-board storage of the data include:

1. Separate A/D's - shared memory
2. MUXed A/D's - shared memory
3. Single A/D
4. Distributed System (separate A/D's, memory)

The analysis of alternative systems was based on the presumption that 0.5 second of data would be required (this encompasses most automotive frontal impact situations). Under this presumption, the volume available inside the dummy for the whole system was marginal at best and such an approach would carry considerable technical risk. Since there is also interest in taking data on tests of much greater duration (up to 5 seconds), the volume demands will be even greater and it does not appear that there will be sufficient volume within the dummy to accommodate both signal conditioning equipment and memory. The alternatives for storing the data off-board (off the dummy) were examined in detail.

With off-board data storage, there are several alternatives. There is the current practice of analog signal transmission and storage of data on magnetic tape. This method usually results in a sizeable umbilical from the dummy and the test vehicle. Even if signals were multiplexed on the dummy, the umbilicals would be smaller but still necessary. Substituting RF telemetry for the umbilical from the test vehicle relieves that problem but results in a system that is overly complex, especially if there are multiple test specimens (i.e., several dummies in a car). This would require several separate telemetry systems with a considerable amount of complex, expensive equipment.

Digital storage on the test vehicle is much more appealing. The alternatives are the same as for the on-board (dummy) storage. In each case the result is a small umbilical from the dummy and none from the test vehicle. This configuration will minimize the number of wires in the umbilical cable, allow for a simpler standard dummy configuration and place no restrictions due to volume on memory size. Initial costs of the dummy will be reduced and reliability increased by locating memory in a less severe environment (shock mounted off the dummy). Design and development costs will also be reduced by not having the difficult problem of packaging memory within the limited confines of the dummy.

Of the available alternatives, the one using separate A/D converters in each data channel is the most appealing for several reasons. The data should be sampled with as little time skewing as possible. While all of the systems can be designed to meet the SAE J211 requirement of 100 usec minimum time skew between any two channels, it may be desirable to have more rigid specifications for such applications as the measurement of angular acceleration with a nine-accelerometer array. In short, it would be advantageous to sample all channels simultaneously. This can be done in each system with a sample and hold (S/H) amplifier in each channel. The system with A/D converters in each channel however, does not require the S/H amplifiers. In the case of simultaneously sampling then, the system with A/D converters in each channel is the system with the smallest chip count and volume. The volume constraints may further be relieved by placing the A/D converters, filters and amplifiers near the associated sensors, leaving centrally located spaces in the thorax, abdomen and pelvis available for the system controller and associated electronics. The system being recommended by TSC is shown conceptually in Figure 2. The data would be sampled by calling for data conversion at the A/D's simultaneously. Data would then be stored (byte by byte) in memory. Pre- and post-calibration routines would be built into the test sequence.

The power distribution subsystem would have to be custom packaged from available components to be compatable with the requirements of the various sensors, amplifiers, A/D converters, etc. The main power source could be a battery riding on the test vehicle.

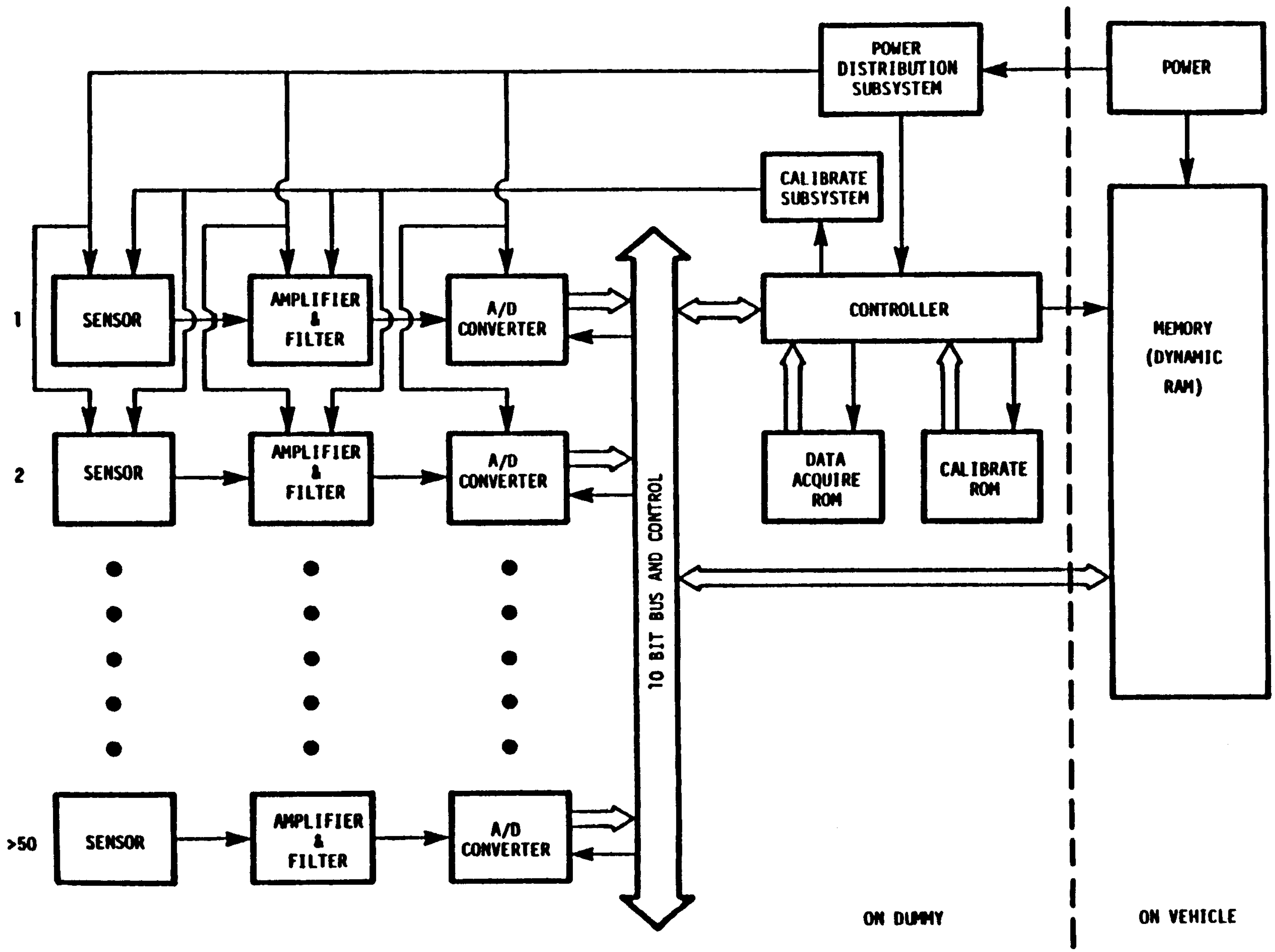

FIGURE 2 - DUMMY INSTRUMENTATION CONCEPT

The calibration subsystem will have to be custom built as well. Pre- and post-calibration, or channel test, is of great importance in the detection of signal drift, dc bias, noise, channel gain, and channel integrity. The calibration subsystem should include the facility to switch shunt resistors for the various strain gage type bridge detectors, voltage levels for injection after other types of sensors to simulate various input levels, and zero levels for each channel. The sequencing of the calibration routine will be performed by the controller using the calibrate read-only-memory (ROM).

As presently conceived, a calibration routine will be initiated prior to the test that will run continuously, storing calibration data for each channel in a small portion of memory. The calibration data would be continuously updated such that the data in memory would always represent the last 50 msec, for example. This would continue until a signal was received indicating the test impact had begun (probably a switch closure). The controller would then run in the data acquisition mode using the data acquire ROM. At the end of a specified time period, data acquisition would cease and the controller would run one more calibration sequence as a post-test calibration. In this manner, offsets or drift in the data channels may be detected and correction factors applied to the data.

The data acquire and calibrate ROM's would be created to match the complement of sensors on the dummy and any particular requirements of the test facility. This could be accomplished with any of a number of programmable read-only-memory (PROM) development systems available. Post-test, the data will be read out and recorded on digital magnetic tape for processing.

Calibration Technology Assessment

TSC currently has an Interagency Agreement with the National Bureau of Standards (NBS) to assess current techniques and develop an optimum methodology for calibrating angular accelerometers. Boundary values placed on the requirements for such a methodology were: (1) an information bandwidth of 1000 Hz, (2) linear acceleration up to 350 g's, and (3) angular acceleration up to 10,000 rad/sec^2. A matrix of the various methods examined and pertinent performance measures is illustrated in Figure 3. Characteristics of several linear shakers that are currently available for use in this effort at the NBS are shown in Figure 4.

The vibrational exciter was determined to be the most critical element in the system. The difficulty lies in achieving the required bandwidth and output simultaneously and maintaining other-mode vibrations at an acceptably low level. There are a number of torsional exciters available which have been developed to test automobile and truck drive trains, propeller shafts and other similar applications. These are generally high torque devices with limited frequency range.

The most cost effective approach to the problem was determined to be the use of a brushless dc servo-motor with an optical shaft encoder. These motors are available in a wide range of specifications and can be matched to the requirements of this project. Optical encoders are capable of 20 bit resolution which corresponds to 1.236 seconds of arc. A small desktop computer would be capable of controlling the experiment and analyzing the data gathered.

Accelerometer System Standard

Work to establish standards for a nine-accelerometer array is being conducted at TSC. The output of a typical piezoresistive accelerometer used in a nine-accelerometer array may be represented as:

$$(1) \quad Q = R_u + \epsilon_1 R_u + \epsilon_2 R_v + \epsilon_3 R_w + \epsilon_o$$

$$+ \epsilon_4 R_u^2 + \epsilon_5 R_{uv} + \epsilon_6 R_u R_w$$

Perf. Measure \ Method	Tangential Acceleration	DSART	Synchro or Resolver	Optical Encoder	Magnetic Encoder	Mechanical Encoder	Reciprocity	Ring Laser Gyro	Optical Interfer.
Freq. Range or Slew Rate	1 - 100 Hz	2 - 100 Hz	5 - 2500 Hz	0 - 5000rpm	0-10000rpm	0 - 750rpm	2 -1000 Hz	0 - 20 kHz	0 - 20 kHz
Dynamic Range	0.5 rad	50 - 8000 rad/s/s	50 -250 rad/s/s	0 - 360 deg limited only by the vib.exciter	0-360 deg	0 -360 deg	0.5 rad	0 -14 rad/s	0 - 1 mrad
Resolution	10 arc-sec	1% of read'g	14 bits	20 bits	14 bits	12 bits	10 arc-sec	2 arc-sec	0.1 arc-sec
Equipment Cost	moderate	high	low	moderate	moderate	low	moderate	high	moderate
Signal-to-Noise Ratio	> 40 dB	> 20 dB	> 40 dB	> 20 dB	> 20 dB	~20 dB	> 40 dB	> 20 dB	> 40 dB
Environmental Sensitivity	normal	normal	resistance to shock	sens. to shock&temp.	robust	res. to shock sens. to temp. &contaminat.	normal	insensitive to envir't	requires controlled environment
State of Development	fully developed	some improv needed	Commercially available except for mounting fixtures. System design will be required.				theoretical basis exists	needs system developm't	not develpd
Note on Cost:	low = < $10,000; moderate = < $50,000; high = > $50,000								

FIGURE 3 - PERFORMANCE CRITERIA MATRIX FOR TORSIONAL ACCELERATION MEASUREMENT

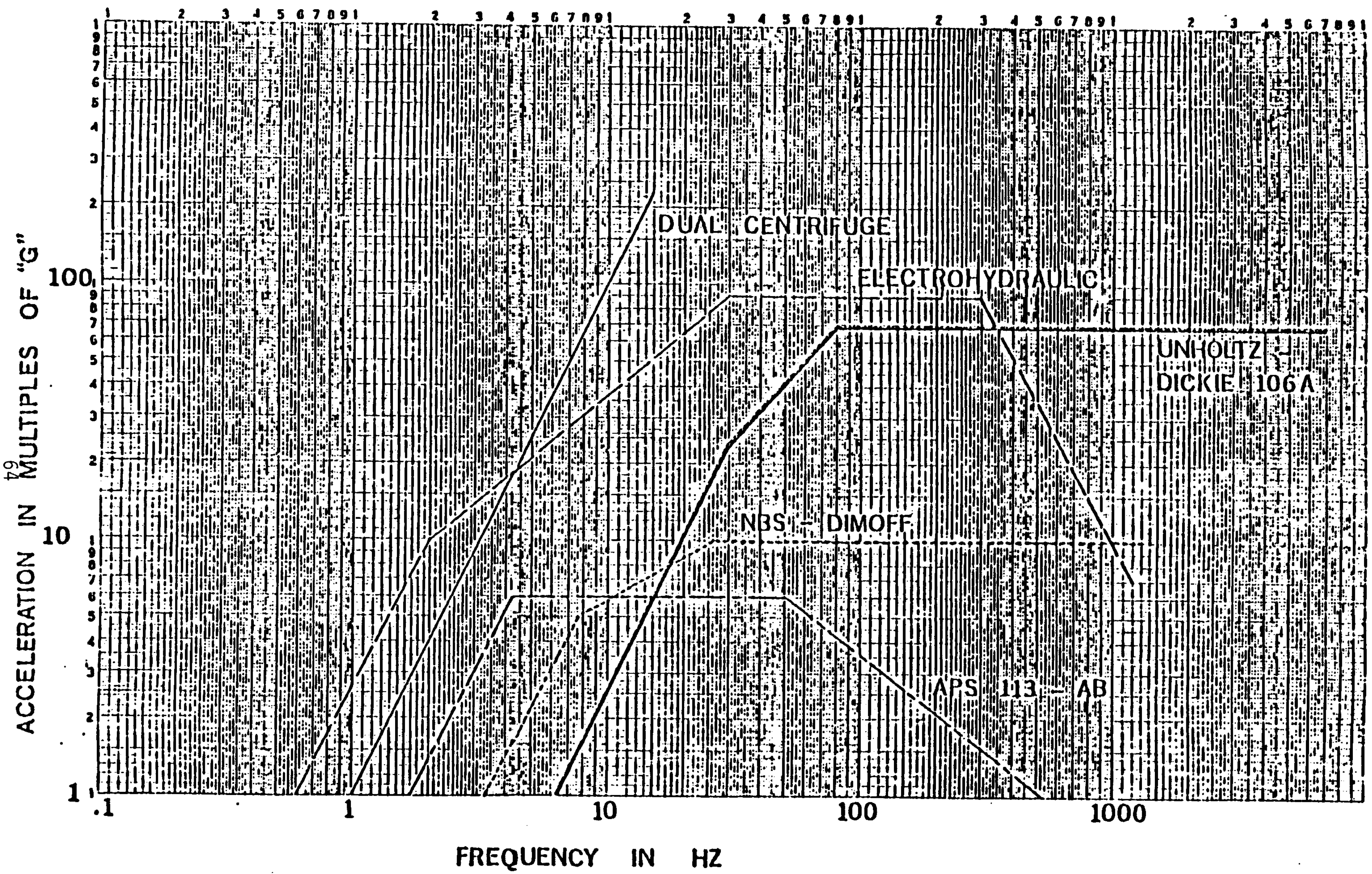

FIGURE 4 - **ACCELERATION CAPABILITIES OF LINEAR SHAKERS**

where:

R_u = acceleration along sensitive axis

R_u & R_w = accelerations in directions perpendicular to sensitive axis

ϵ_o = bias error

ϵ_1 = uncertainty in accelerometer scale factor

ϵ_2 & ϵ_3 = cross axis sensitivities

ϵ_4, ϵ_5 & ϵ_6 = sensitivities to acceleration squared effects.

The error terms of particular interest and most troublesome are ϵ_o (bias) and ϵ_1 (scale factor uncertainty). Recent reports from Wayne State University have indicated that there exist shifts in accelerometer sensitivity at low frequencies. This shift is represented by the scale factor error term and may degrade the data on angular acceleration considerably. To examine the effects of some of these error coefficients a number of simulations were performed. With the 3-3-3 configuration the signals obtained have the following form.

$$Q_z = \dot{\omega}_z$$

$$Q_y = \dot{\omega}_y + \omega_x \omega_y$$

$$Q_x = \dot{\omega}_x - \omega_y \omega_z$$

In theory, these equations can be solved by numerical integration to determine the angular velocities. The simplest integration scheme would be:

$$\dot{\Omega}_{z_i} = Q_z$$

$$\dot{\Omega}_{y_i} = Q_y - \Omega_{x_{i-1}} \Omega_{z_{i-1}}$$

$$\dot{\Omega}_{x_i} = Q_x - \Omega_{y_{i-1}} \Omega_{z_{i-1}}$$

$$\Omega_{x_i} = \Omega_{x_{i-1}} + \dot{\Omega}_{x_i} \Delta t$$

$$\Omega_{y_i} = \Omega_{y_{i-1}} + \dot{\Omega}_{y_i} \Delta t$$

$$\Omega_{z_i} = \Omega_{z_{i-1}} + \dot{\Omega}_{z_i} \Delta t$$

where $\dot{\Omega}_i$ is the estimated angular acceleration at the i^{th} time step of Δt. The integration method used is a simple trapezoidal, forward-difference routine. Using this methodology a number of simulations were performed. Figure 5 represents the output of a nine-accelerometer system with a initial bias of 50 rad/ sec^2. The integration sample rate in this case was 1 MHz. It can be seen that there is little change for the first 200 msec. After that, however, error growth increases rapidly and oscillates about zero. Figure 6 illustrates the error growth if the initial bias is 100 rad/ sec^2. It can be seen that the relatively quiescent period in the beginning is shorter and the error growth and frequency of oscillation is greater.

Of course, a 1 MHz integration sampling rate is unreasonable since the data is gathered at a much lower sample rate. The sample rate recommended in SAE J211 is 8 KHz. Figures 7 and 8 represent output with initial biases of 50 and 100 rad./sec^2 respectively done with an integration sampling rate of 8 KHz. Comparing Figure 8 with Figure 6, one can see that the error growth is greater with the lower sampling rate. This is not as apparent in the comparison between Figures 5 and 7 with a lower initial bias. Since field data has actually been taken in the past at a sampling rate of 2000 Hz, runs using

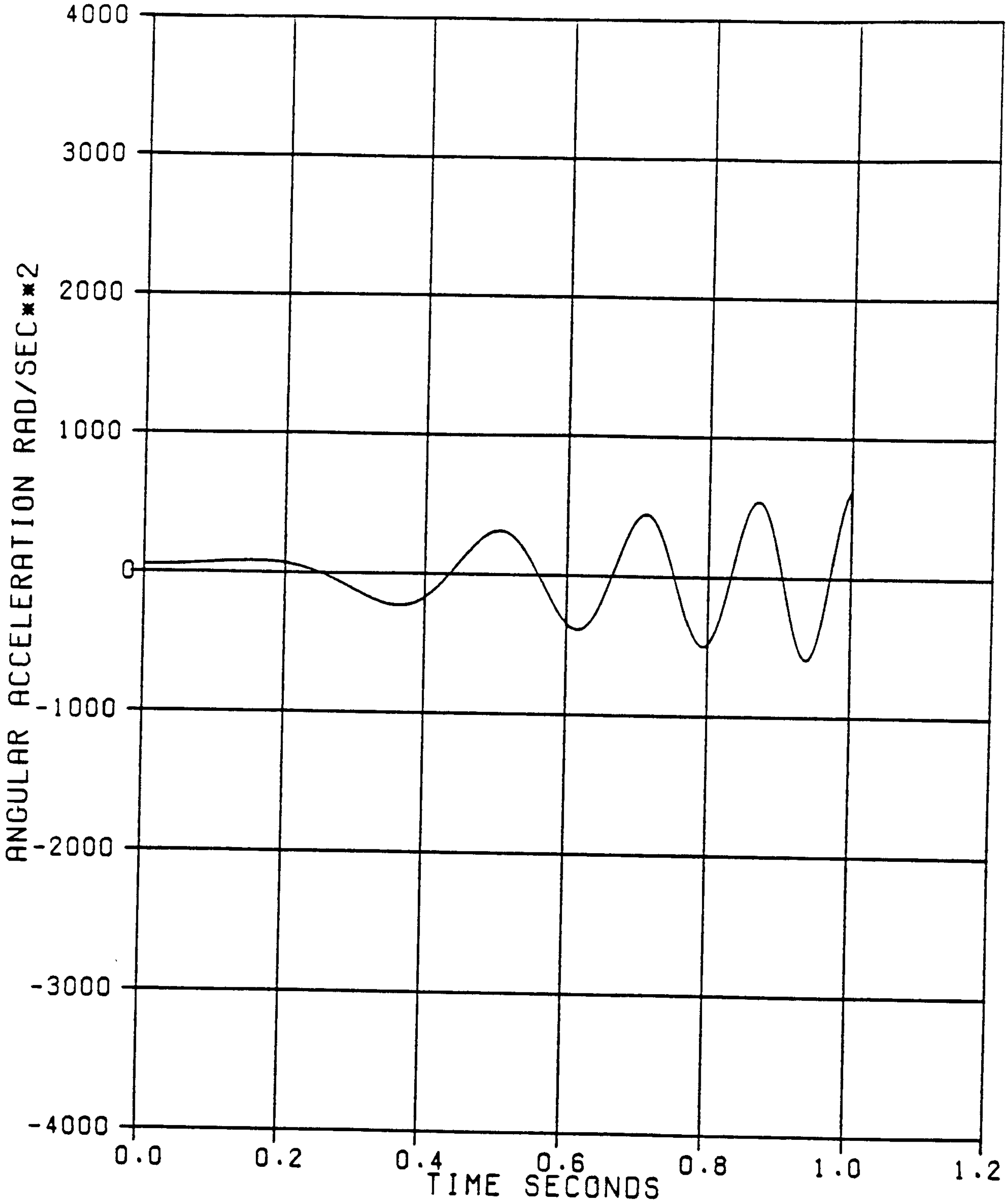

FIGURE 5 : 1,000,000 HZ. SA MPLE RATE
50 RAD/SEC**2 CASE

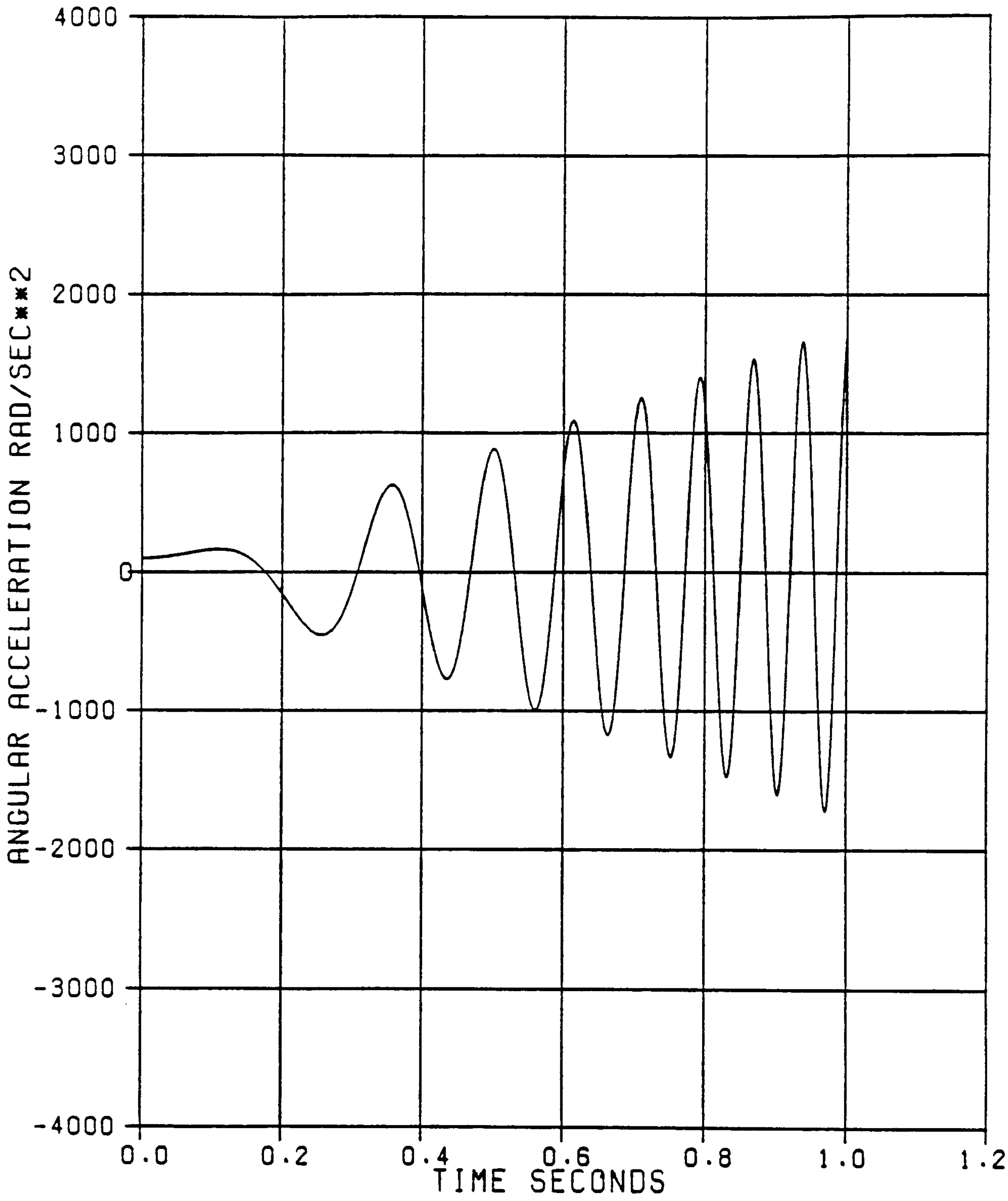

FIGURE 6 : 1,000,000 HZ. SAMPLE RATE
100 RAD/SEC**2 CASE

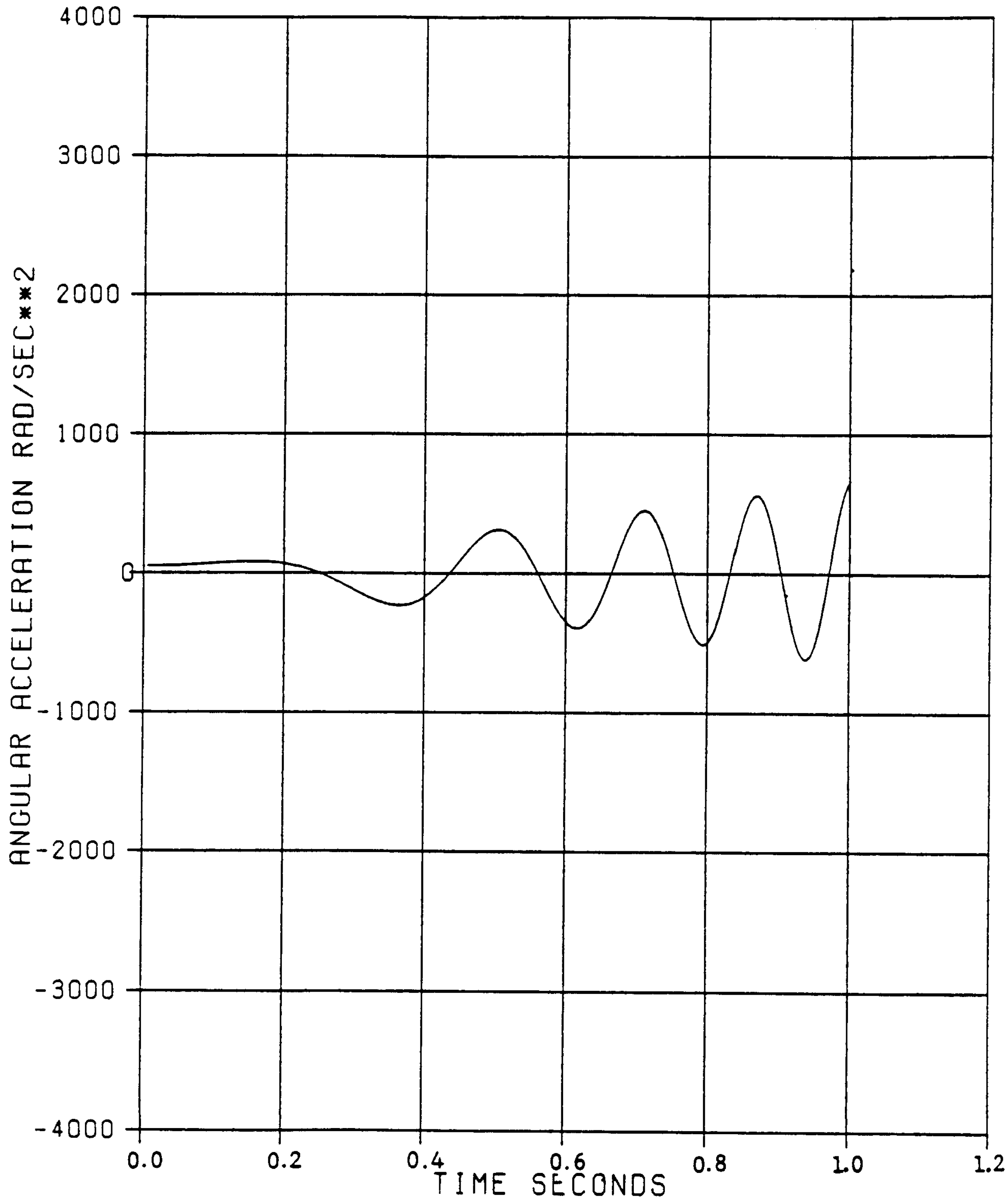

FIGURE 7 : AE50.DAT

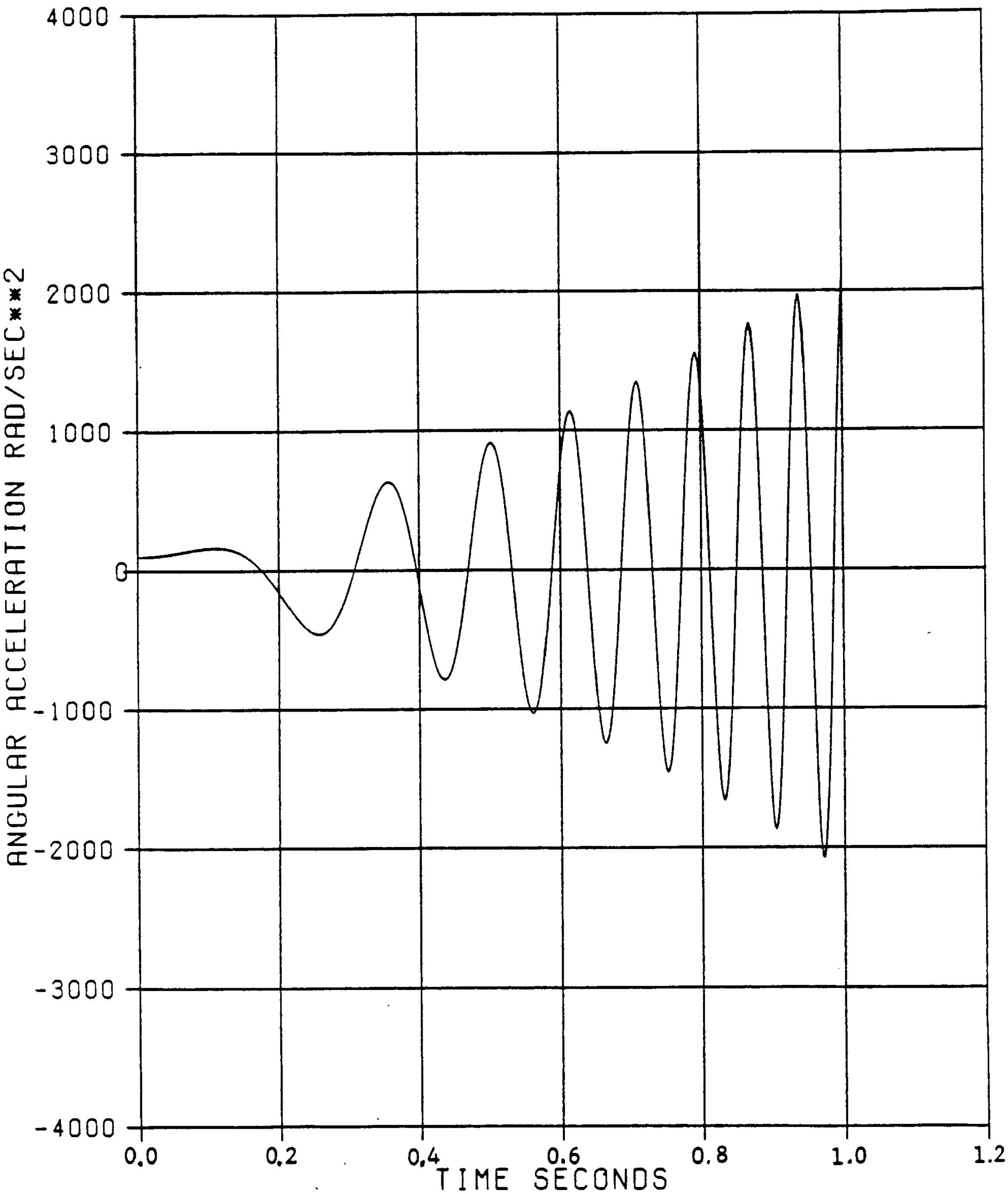

FIGURE 8 : AE100.DAT

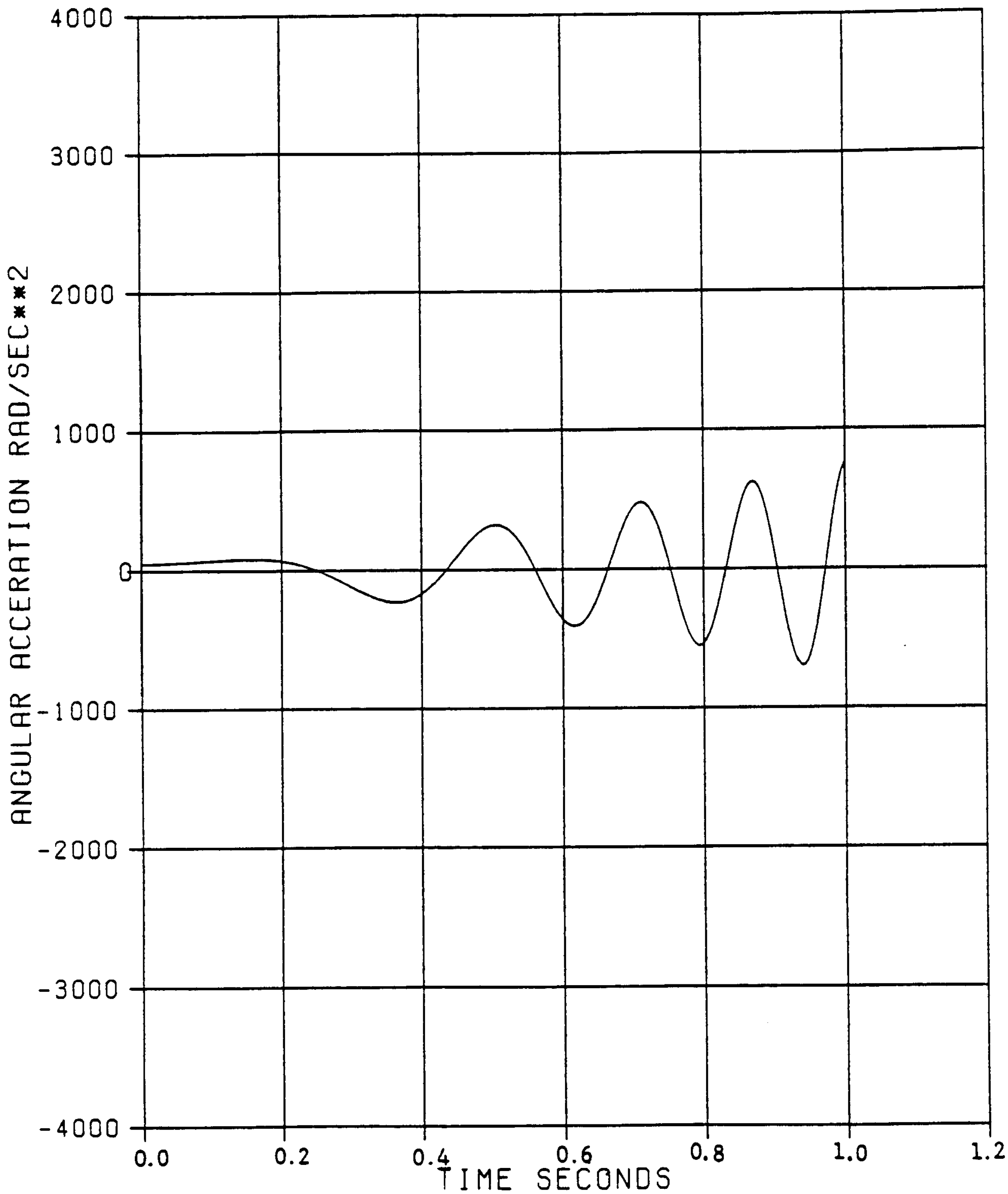

FIGURE 9 : C2000.50

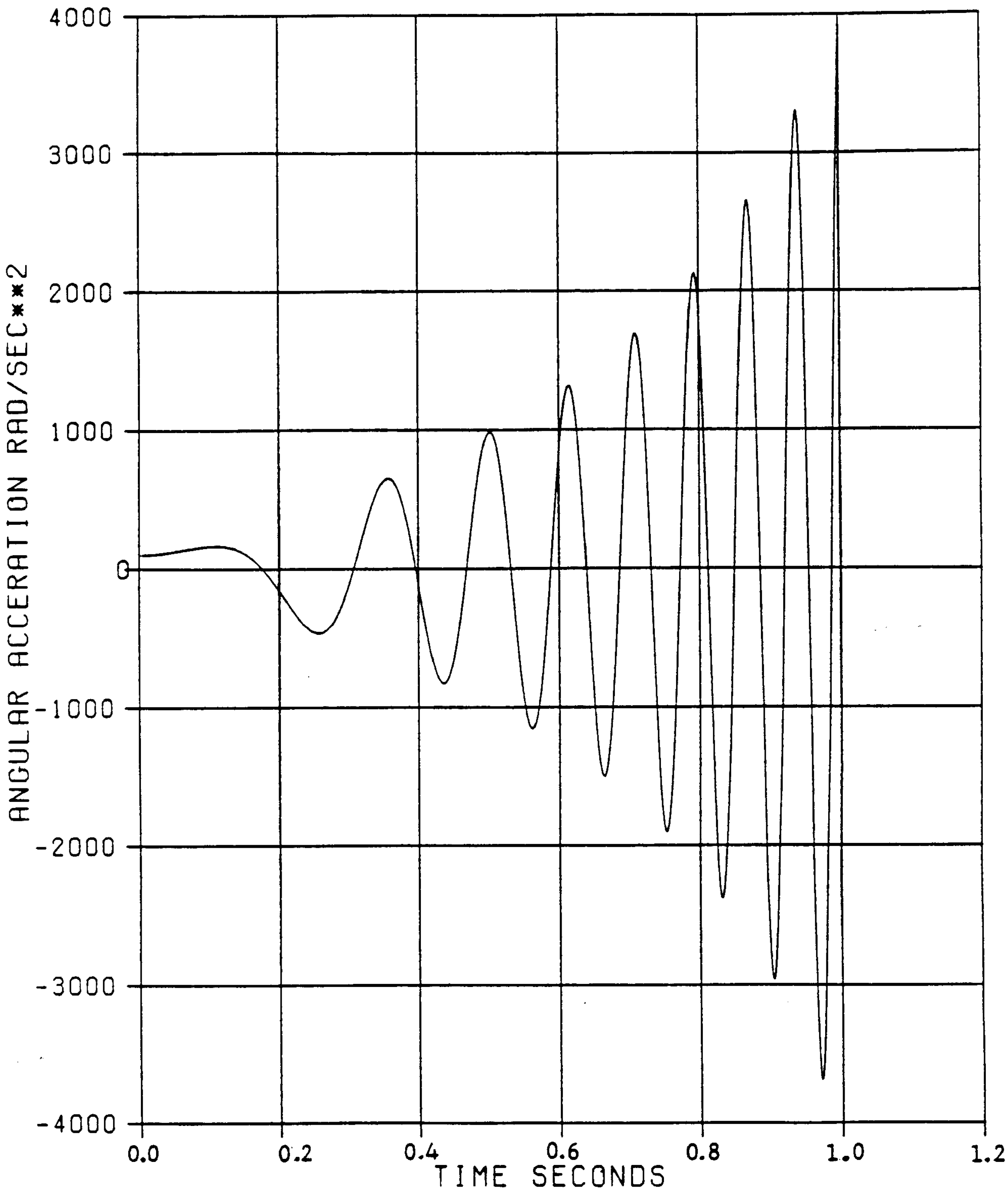

FIGURE 10 : C2000.100

this rate for integration were made, and the results are illustrated in Figures 9 and 10. Figure 10 shows a dramatic increase in the error growth. In ever case however, the system response in the initial 200 msec. appears to be independent of the sample rate and quite dependent upon the initial bias. This evidence is a strong argument for measuring only pulses of short duration and attempting to maintain initial biases as low as possible.

The next logical question was what effect will this error growth have on an actual input pulse. As the evidence from Wayne State University has indicated that there can be considerable sensitivity mismatch at low frequencies among the accelerometers in the array, an investigation of this effect was performed. For the purpose of the simulation, a sensitivity mismatch of 5% between principal pairs of accelerometers was assumed. To effect the simulation, a linear half sine acceleration, 100g in amplitude and 10 msec. in duration was used. If this pulse were input along the sensitive axis of a principal pair of accelerometers in the nine accelerometer array, the resulting output would be an apparent angular acceleration of 241 rad/sec^2 of 10 msec duration. If, on the other hand, a linear acceleration were applied to the 3-3-3 system at an oblique angle such that each principal axis experienced a linear acceleration of 100g, the resulting output for any axis will include an error growth element. This situation is illustrated in Figure 11. For such a short pulse duration, the accumulated error is very small, and the pulse almost returns to zero at 100 msec., as it should. The situation changes dramatically when the duration of the input pulse is increased to 100 msec. This is illustrated in Figure 12. The initial rise shows considerable overshoot to over 300 rad/sec^2 (should only go to 241 rad/sec^2) and beyond 100 msec., oscillates with an increasing magnitude. Still further evidence that the 3-3-3 configuration should only be used to measure short duration pulses. Future work in this area will include additional simulations, such as those illustrated here in order to gather quantitative information that can be used to develop specifications for a standard nine-accelerometer array.

As mentioned earlier, work at Wayne State University indicated that some of the more commonly used transducers exhibited significant sensitivity variations at low frequencies. In particular, it was shown that an ENDEVCO Model 2264-200 accelerometer can exhibit an increase in sensitivity at low frequencies (<100 Hz) of up to 5%. Similar results were obtained in tests of accelerometers manufactured by ENTRAN Devices, Inc. Shifts in sensitivity of this order virtually eliminate these

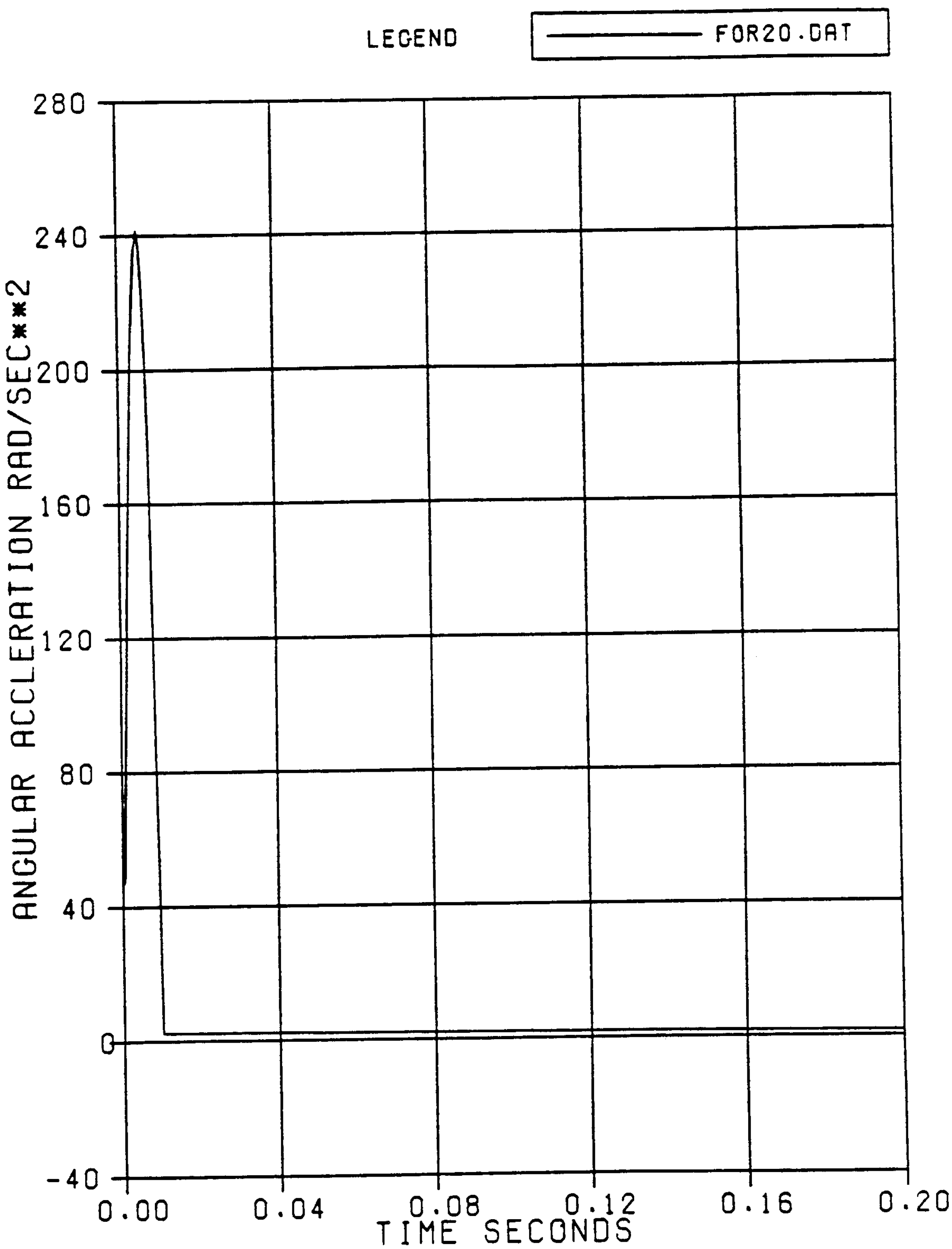

FIGURE 11 : 3-3-3 8000 HZ. 100 G 10MSEC PULSE PULSE OUT OF PLANE

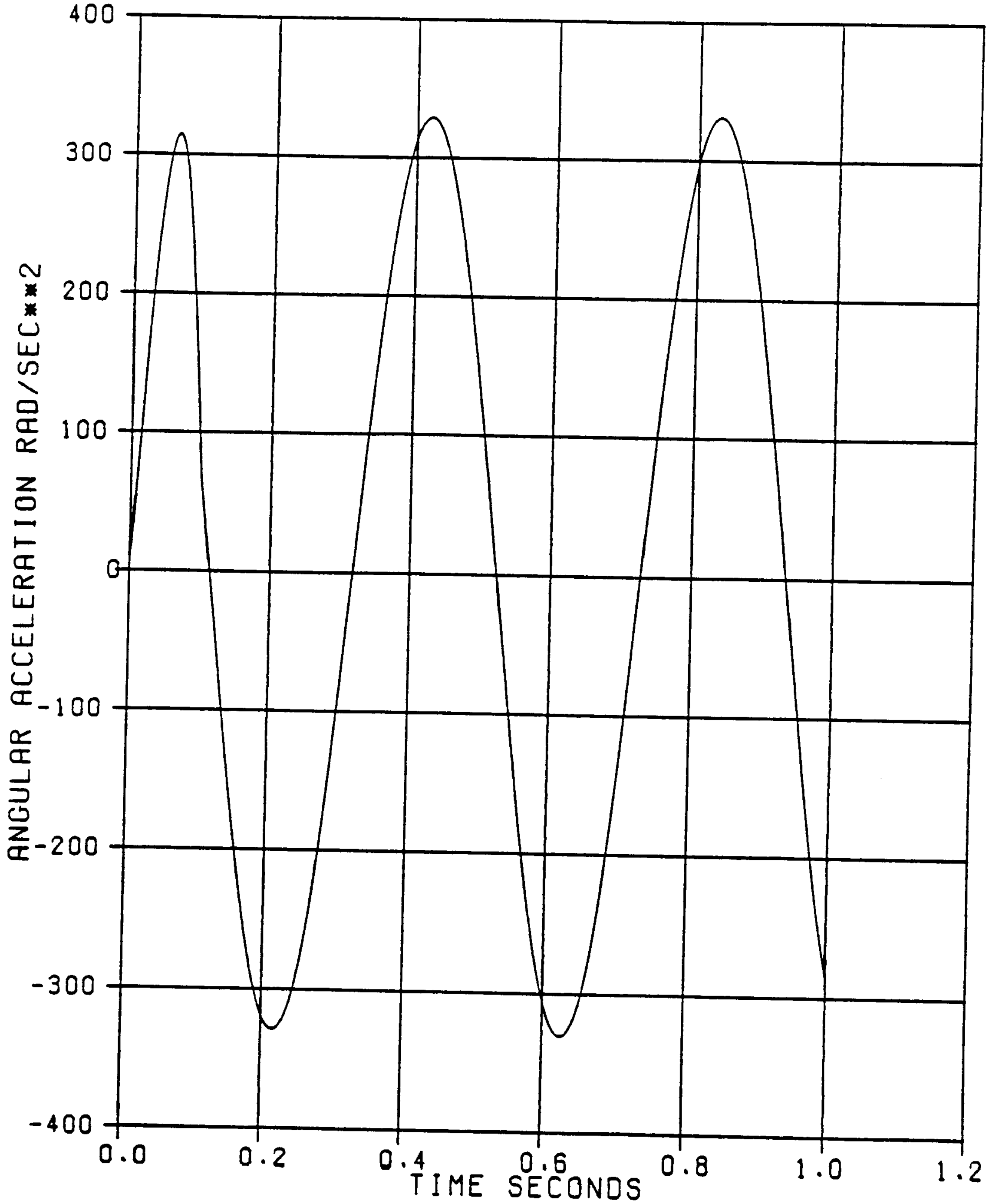

FIGURE 12 : 100 MSEC 241 RAD/SEC**2
C100MS.241

accelerometers as suitable for use in a nine-accelerometer array for measuring angular and linear acceleration. To further examine this phenomenon, two (2) accelerometers were calibrated at the National Bureau of Standards (NBS) using the NBS-Dimoff shake table there. The results of these calibrations (not an official NBS calibration) are shown in Figures 13 and 14. The ENDEVCO Model 2264-2000 shows (Figure 13) a variation in sensitivity of up to 8.5% over the frequency range of 30 Hz to 1000 Hz. This accelerometer had been used previously however, and may have been damaged. On the other hand, the ENDEVCO Model 7264-2000 shows (Figure 14) a very flat response which, if the measurement at 300 Hz is discarded (erroneous data often appears at 300 Hz on this shaker system as it is a multiple of line frequency), varies less than 2.5% over the same frequency range. This transducer would be much more suitable for use in a nine-accelerometer array than the Model 2264-2000. Wayne State has also reported to us that the Kistler " picotron" piezoelectric accelerometer has an acceptable low frequency response and has suggested that these be used in the array. A calibration of this transducer is planned and the final decision on which accelerometer to use with the nine-accelerometer array will come from discussions of the results of these calibrations with NHTSA personnel.

Acknowledgment: The accelerometer systems analyses and simulations were performed by Dr. H. Weinstock, M. Coltman, and H. Lee of the Transportation Systems Center, Research and Special Programs Administration, U.S. Department of Transportation.

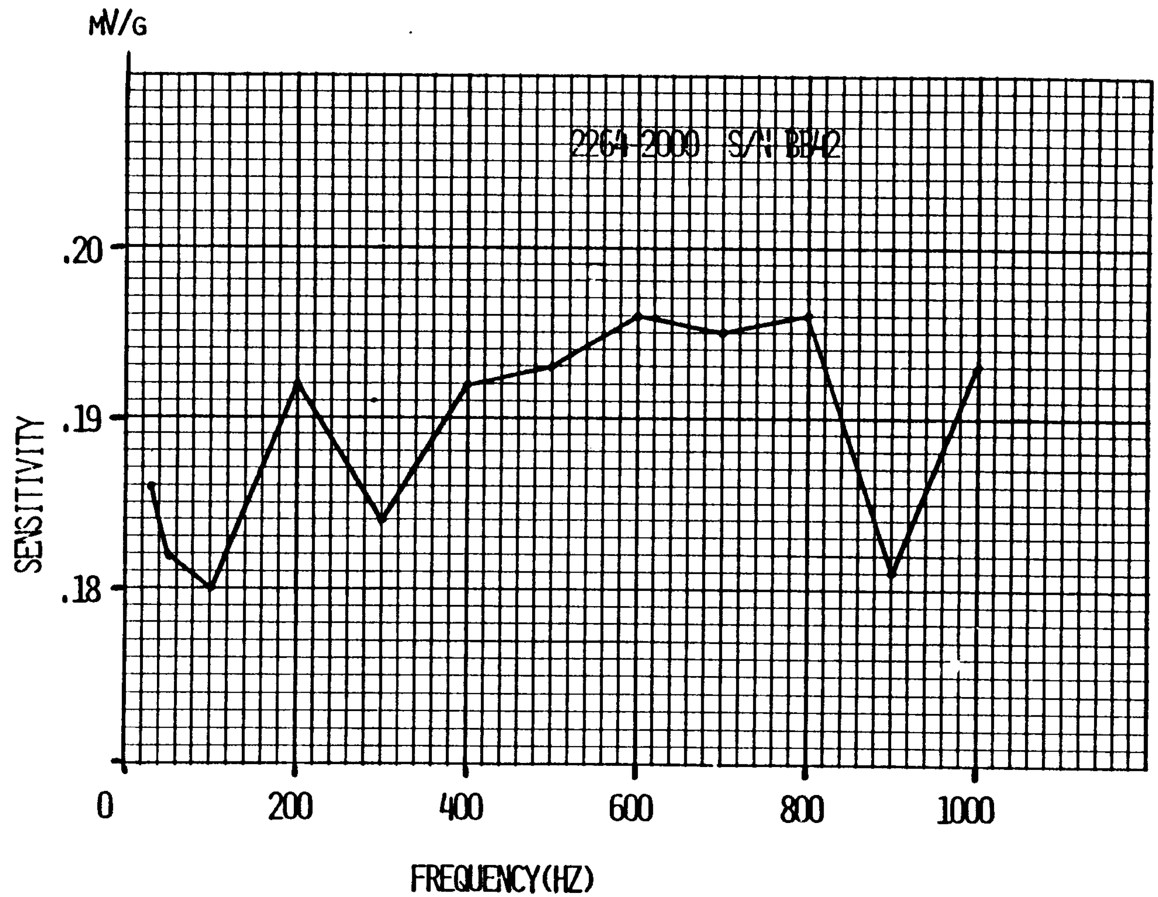

FIGURE 13 - SENSITIVITY OF ENDEVCO MODEL 2264-2000

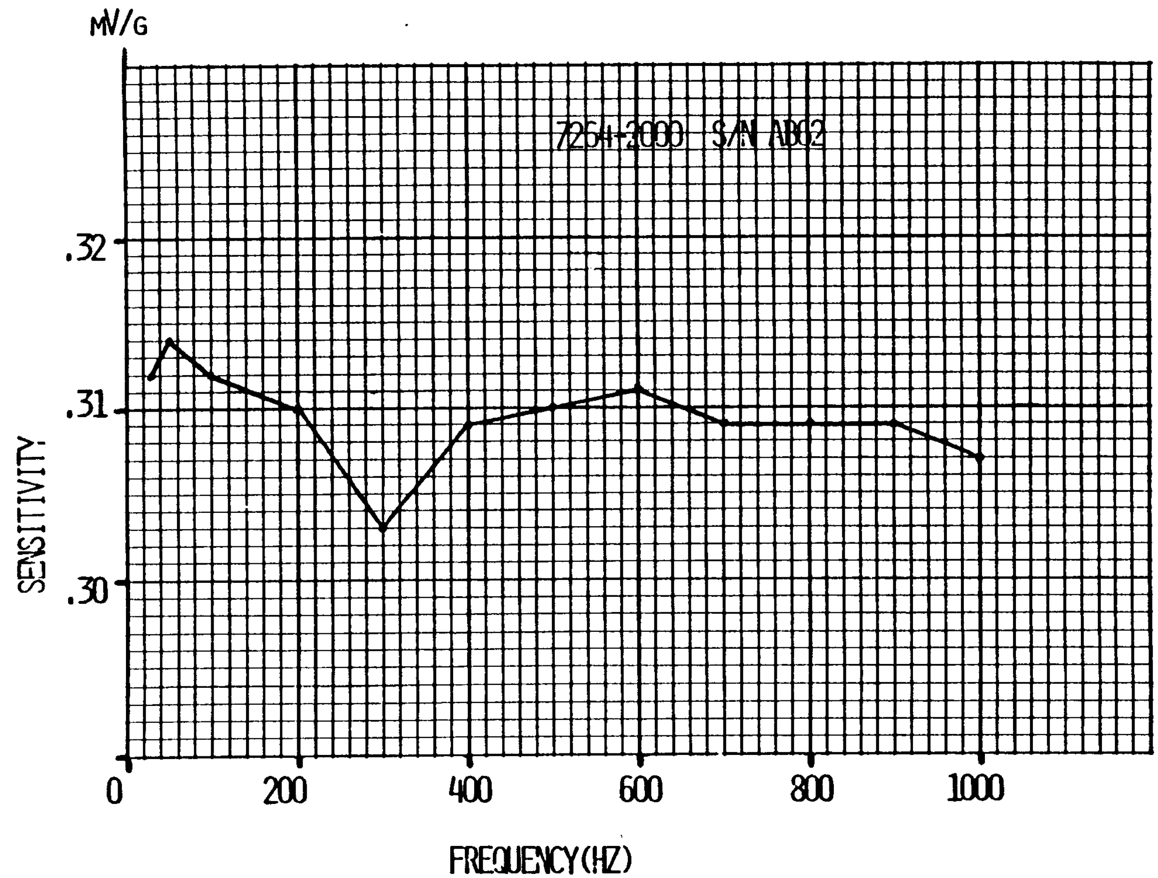

FIGURE 14 - SENSITIVITY OF ENDEVCO MODEL 7264-2000